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Review of international grid codes for wind power integration: Diversity, technology and a case for global standard

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ABSTRACT

This paper presents a comprehensive study on the latest grid code regulations enforced by transmission system operators on large wind power plants (WPPs). First, the most common requirements included in the majority of international grid codes are compared; namely, low and high voltage ride-through capabilities, active and reactive power responses during and after faults, extended range of voltage–frequency variations, active power (frequency) control facility, and reactive power (voltage) regulation support. The paper also presents a discussion on the global harmonization of international grid codes as well as future trends expected in the regulations. Finally, the evolution of different wind generator technologies to fulfill various grid code requirements is investigated. The presented study will assist system operators to establish their connection requirements for the first time or to compare their existing regulations with other operators. It also enables wind turbine manufacturers and wind farm developers to obtain a more precise understanding from the latest international requirements imposed on modern wind farms.

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Contents

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Table 1
Grid codes under study.

System operator	Country	Last revision	Website
Energinet	Denmark	September 2010	www.energinet.dk
REE	Spain	October 2008	www.ree.es
Transpower and E.ON	Germany and Deutschland	October 2010	www.tennettso.de
AEMC	Australia	July 2011	www.aemc.gov.au
National Grid	Great Britain	August 2011	www.nationalgrid.com
EirGrid	Ireland	March 2011	www.eirgrid.com
FERC	USA	June 2005	www.ferc.gov
AESO	Canada (Alberta)	November 2004	www.aeso.ca
Hydro Quebec	Canada (Quebec)	May 2003	www.hydroquebec.com
Nordel	Nordic Countries	January 2007	www.entsoe.eu
Vreg	Belgium	December 2009	www.vreg.be

1. Introduction

Grid code regulations are defined by system operators to outline the rights and responsibilities of all the generators and loads that are connected to the transmission/distribution system. In the past, grid codes did not include any regulations for WPPs because the penetration level of wind power was extremely small compared to the conventional generation systems. However, the situation has radically changed during the last decade as many countries witnessed tremendous increase in the number and capacity of WPPs integrated into their electric networks. The shift from conventional to the renewable energy resources has raised serious concerns regarding the negative impacts of large WPPs, as intermittent generation units, on the stability of existing power networks. To safeguard the network against these threats, system operators in many countries have enforced stringent technical requirements on large WPPs. Modern grid codes require WPPs to not only withstand various grid disturbances, but also contribute to the network stability support and ancillary service provision, as do conventional generation units [1].

The issue of grid code requirements for large wind farms has been already explored in the literature. The US federal and regional grid codes were presented in [2]. Technical regulations of Canada, Germany, Ireland, UK and Spain were studied in [3–7], respectively. Comparative study of the international grid codes was first reported in [8], evaluating Danish, British, German, and Irish Grid Codes. Similar comparative studies were reported in [9,10]. The most recent comparison of the international regulations was conducted in 2009 [11], comparing the technical requirements of Belgium, Canada, Denmark, Germany, Ireland, New Zealand, Norway, Spain, Sweden, UK and USA.

However, grid codes are subject to continuos changes and new requirements (such as high-voltage ride-through, reactive current injection, and power system stabilization) were just assimilated in some grid codes within the last few years. Hence, an updated comparison of the international grid codes can be very beneficial for network operators as well as wind turbine manufacturers. This study would help system operators to evaluate their requirements versus other international operators. It also assists new system operators to start establishing their technical requirements based on the regulations of countries that already have extensive experience from the operation of power systems with large wind power levels, such as Germany and Denmark. It is however obvious that each country must tailor its grid code based on its wind power level, robustness of existing network, and local utility practices. On the other hand, comparison of the international grid codes will enable wind turbine manufacturers and wind farm developers to obtain a more precise understanding from the latest international regulations, which in turn, strengthens their competency in the global wind turbine market with the annual turnover of 70 billion USD [12].

This paper presents a thorough comparison of the international grid codes enforced on large WPPs. The countries with significant wind power level are considered, as listed in Table 1. It must be noted that this paper concentrates on the technical regulations that apply to large wind farms, rather than those related to small wind farms connected to distribution systems. That is, the regulations on the wind farm response to various grid disturbances and their ancillary service provision are only investigated, based on the fact that technical regulations on power quality, fault level contribution, and anti-islanding protection are only of main concern for small WPPs with the rated power smaller than 10 MW [1,8–11].

This paper is organized as follows. In Section 2, the most common grid code requirements included in majority of international grid codes are explored. Section 3 compares the most common technical regulations, followed by discussing about the global harmonization of grid codes and future trend of the regulations in Section 4. The issue of emerging grid compliant solutions for different wind generator technologies is studied in Section 5.

2. Review of the grid connection requirements

A review of the international grid codes shows that the technical requirements enforced on large WPPs can be broadly classified into five groups: (1) fault ride-through requirements, (2) active and reactive power responses following disturbances, (3) extended variation range for the voltage–frequency, (4) active power control or frequency regulation support, and (5) reactive power control or voltage regulation capability.

When a fault occurs at some points in the electric network, the supply voltage drops to the lower levels until protection devices detect the faulty area and isolate it from the rest of the network. During this interval, wind generators, like other system components, experience a voltage sag condition at their terminals depending on the type and location of the fault. As a result of this disturbance, wind farms (specifically those employing modern variable-speed technologies) may disconnect from the grid due to severe stability problems. A practical example of this incident was experienced in the European outage on 4 November 2006, which caused losing 4892 MW of wind power generation in Western-Europe [13].

The disconnection of WPPs under voltage disturbances is unacceptable when wind power constitutes a significant part of the total network generation. Thus, modern grid codes require WPPs to continue their uninterrupted operation under various fault conditions according to given voltage–time profiles. Such requirements are usually referred to as low voltage ride through (LVRT) capability. Fig. 1 shows a practical example of the LVRT curve defined by the Danish system operator for wind generators connected to the transmission system ($V > 110$ kV): "a wind power plant shall remain connected to the transmission system under fault conditions when the voltage measured at the HV terminals of the grid connected

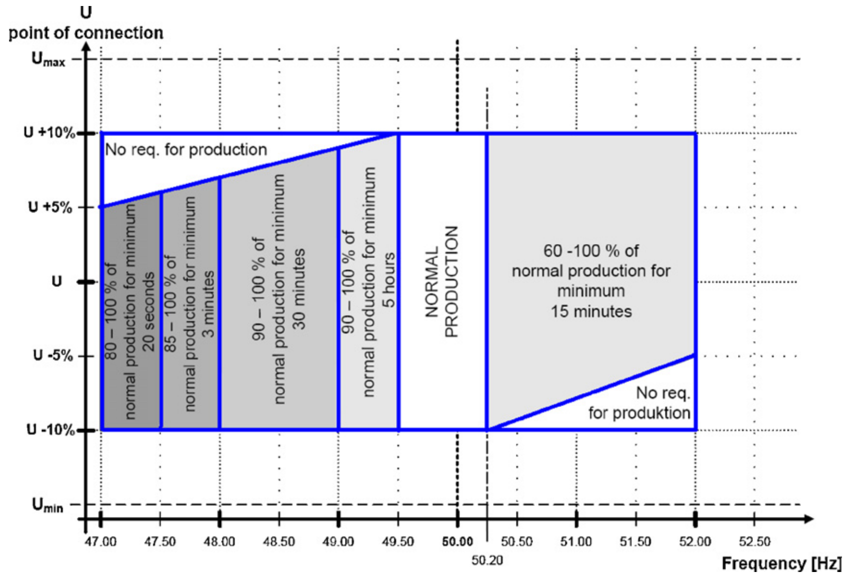

Fig. 2. Normal operation area as defined by Danish Grid Code.

transformer (point of common coupling – PCC) remains in *Area B* shown in Fig. 1" [14]. That is, WPPs are only allowed to disconnect from the grid when the voltage profile falls into *Area C*.

Some international grid codes also require large WPPs to continuously operate under small deviations of the voltage magnitude or frequency. This range of variations is usually referred to as 'the normal operation area', as shown in Fig. 2 for Danish Grid Code. From Fig. 2 it is clear that WPPs must retain at least 60% of their normal production for 15 min when the frequency varies between 50.2 Hz and 52 Hz and the PCC voltage changes in the range of ±10%.

In the very recent years, grid codes of some countries like Australia, Denmark and Spain have enforced demanding voltage–time profiles for voltage swell conditions. Voltage swells could be initiated by switching off large loads, energizing capacitor banks, or occurring faults in the grid. This requirement is commonly referred to as high voltage ride-through (HVRT) capability. The Australian HVRT curve, for instance, is shown in Fig. 3 [15]. Modern grid codes may also require large WPPs to withstand frequency excursions that can be observed under grid disturbances with large mismatch between the generation and consumption in the system.

Besides the LVRT and HVRT requirements, some international grid codes require large WPPs to provide reactive power support during the fault period and/or exhibit fast active power recovery during the supply voltage restoration. These regulations are enforced to fully exploit the control capability of modern wind farms and contribute to the system stability support following various grid disturbances. For instance, Danish Grid Code requires large WPPs to support the transient voltage stability of the network through providing the reactive current according to the characteristic shown in Fig. 4: "as the PCC voltage drops by more than 10%

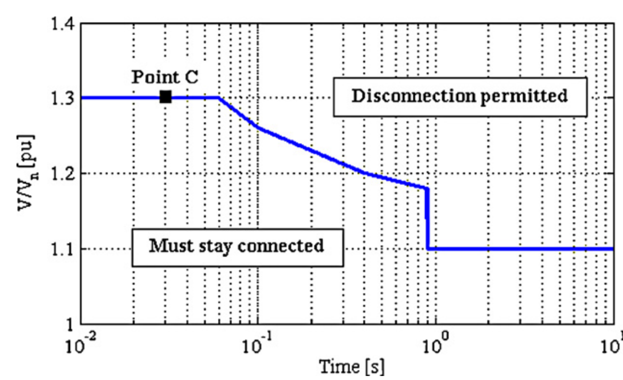

Fig. 3. Australian HVRT requirement.

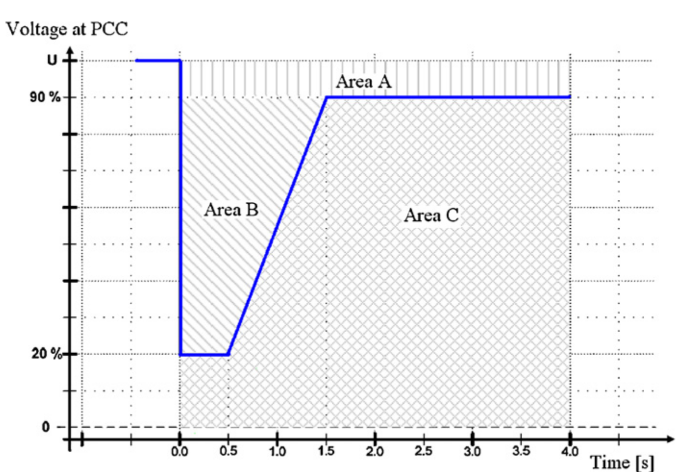

Fig. 1. Danish LVRT requirement.

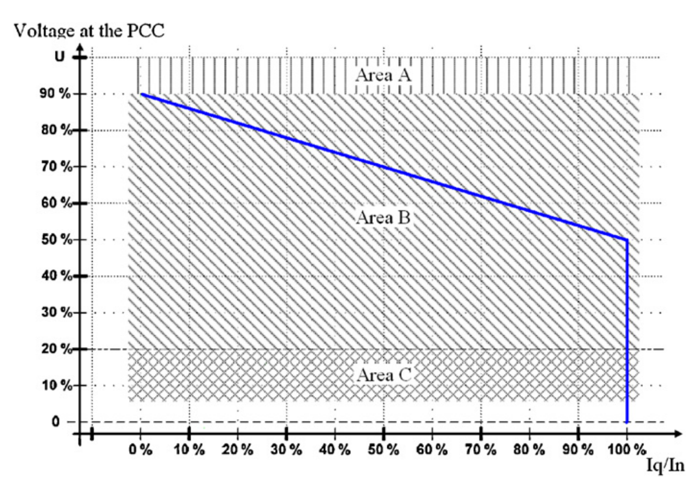

Fig. 4. Reactive power support requirement enforced by Danish Grid Code.

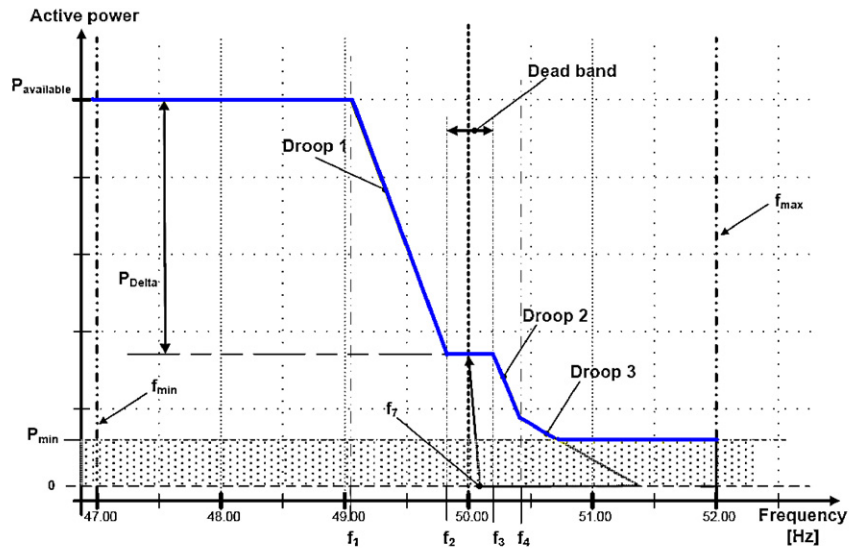

Fig. 6. Power–frequency response curve requested by Danish Grid Code.

(i.e., operating within *Area B* in Fig. 1), the reactive current output of the WPP must follow the characteristic shown in Fig. 4 – with a tolerance of ±20% in 100 ms". It can be seen that the I_Q component of the WPP must increase by 2.5% (on a PU base) for each 1% drop in the PCC voltage. The injection of reactive power has the highest priority in *Area B*, but the free capacity of current must also be utilized to retain the active power production in proportion to the voltage sag magnitude. Furthermore, the Danish TSO stipulates active power restoration to the pre-fault value immediately after the fault clearance.

Apart from the regulations on the transient response of large WPPs, network operators usually demand large WPPs to actively participate in the ancillary service provision. Large WPPs, in particular, must be able to control their active power output and thereby, provide short- and long-term frequency supports to the network. Danish Grid Code has recommended two practices to manage the active power production of large WPPs: *delta production constraint* and *power gradient constraint* (as graphically demonstrated in Fig. 5). The former practice can be applied by limiting the active power from the WPP to a constant value in proportion to the available active power. The resulting spinning reserve power could be readily used to perform primary frequency control in the case of frequency drop. The power gradient constraint, on the other hand, will limit the maximum speed by which the active and reactive powers of WPP can change in the event of changes in wind speed or the

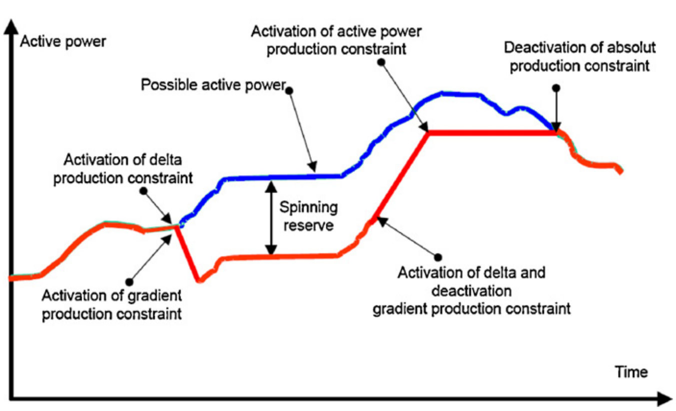

Fig. 5. Delta production constraint and power gradient constraint recommended by Danish Grid Code.

setpoints of the WPP. This control action is needed from system operation point of view to prevent sudden changes in the output active power which can potentially disturb the network stability.

Fig. 6 shows the typical power–frequency response curve requested by Danish Grid Code: "when the grid frequency deviates from 50.00 Hz, WPPs must be able to provide active power control to stabilize the grid frequency at its nominal value according to characteristic shown in Fig. 6". The control scheme adopted in the WPP must be able to set the frequencies $f_{\min}$, $f_{\max}$, as well as f_1–f_7 to any value in the range of 50.00 Hz ± 3.00 Hz with an accuracy of 10 MHz. The purpose of frequency points f_1–f_4 is to form a dead band and a control band for primary control. The purpose of frequency points f_5–f_7 is to supply critical power (frequency) control." Note that in Fig. 6, P_{Delta} is the setpoint to which the available active power has been reduced in order to provide primary frequency stabilization (upward regulation) in the case of frequency drop. Various drop slopes (Droop 1 to Droop 3) can be suggested under various operating conditions.

Besides the frequency support, large WPPs must be capable of providing the voltage regulation facility by continuously operating at a range of capacitive/inductive power factor. Fig. 7 shows typical requirement on the reactive power and power factor control of a wind farm, enforced by Danish Grid Code. It requires WPPs to operate with a power factor interval of 0.95 capacitive to 0.95 inductive when the WPP production constitutes more than 20% of the rated power. Besides that, WPPs must be designed in such a way that the operating point can lie anywhere within the hatched area in Fig. 8 to assist steady-state voltage regulation.

3. Comparison of the international grid codes

3.1. Fault ride-through requirement

The LVRT curves included in the international grid codes are relatively similar to Fig. 1, although their quantitative characteristics may vary from one system operator to another. From Fig. 1 it can be seen that Danish Grid Code requires WPPs to withstand faults with voltage drop down to 0.2 PU for 0.5 s, followed by the voltage restoration to 0.9 PU during the next 1.0 s. Australian Grid Code outlines more onerous LVRT curve which requires WPPs to ride-through symmetrical and asymmetrical sags with the voltage down to zero for 150 ms and 400 ms, respectively. The supply voltage must then restore to 0.7 PU within 2 s and to 0.8 PU within 10 s.

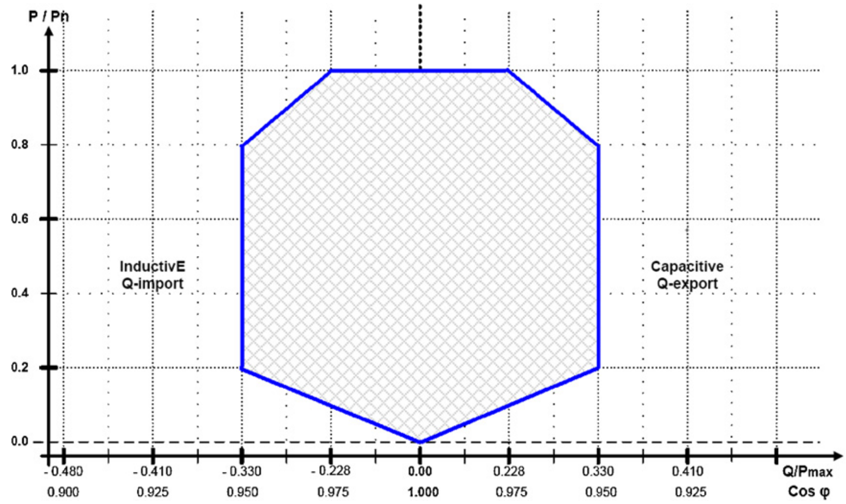

Fig. 7. Reactive power and power factor requirements enforced by Danish Grid Code.

German Grid Code imposes no requirements for asymmetrical voltage sags, but requests ride-through capability for three-phase faults with the voltage drop to zero for the maximum duration of 150 ms, followed by the voltage recovery to 0.8 PU in 1.5 s (as shown Fig. 9). The older version of the German LVRT curve is now adopted in Ireland and USA. This curve has the minimum voltage of 0.15 PU for 0.625 s and the voltage recovery period of 3 s, as shown in Fig. 10. The parameters of LVRT curves for other grid codes are summarized in Table 2.

Table 2 shows that the most onerous LVRT requirement are enforced by the Australian Grid Code, which demands continuos operation of WPPs under asymmetrical sags with the voltage down to zero for 400 ms. For symmetrical sags, on the other hand, the grid codes of Australia, Canada, Denmark, Germany, New Zealand, Spain and USA (WECC) have similar requirements. It is also worth noting that if the typical impedance values for the step-up transformers and interconnecting lines inside the wind farms are taken into account, the minimum voltage sag at the terminals of wind generators are very likely to be above 0.15 PU [6]. This will obviously facilitate compliance with the LVRT requirements as the voltage at the wind generators terminals will be higher than the PCC.

The HVRT capability has been requested in the grid codes of Australia, Denmark, Spain, Germany and USA. The Australian Grid Code presents a HVRT characteristic curve as shown in Fig. 2. However, this requirement in other grid codes is given only quantitatively. Table 3 compares the HVRT requirements of various grid codes. It is evident that the Australian and Spanish Grid Codes have the most onerous HVRT regulations that require WPPs to withstand voltage swell of 1.3 PU.

3.2. Active and reactive power responses of WPPs under network disturbances

In countries with large penetration level of wind power or countries with weakly interconnected networks, grid codes enforce stringent regulations on the active/reactive power responses of large WPPs during and after faults in the network. These strict regulations are set to secure the system stability following various types of disturbances. Regulations on the active power response of WPPs assist the network to maintain its short-term frequency stability while the reactive power support from WPPs can reinforce the voltage stability limits of the network.

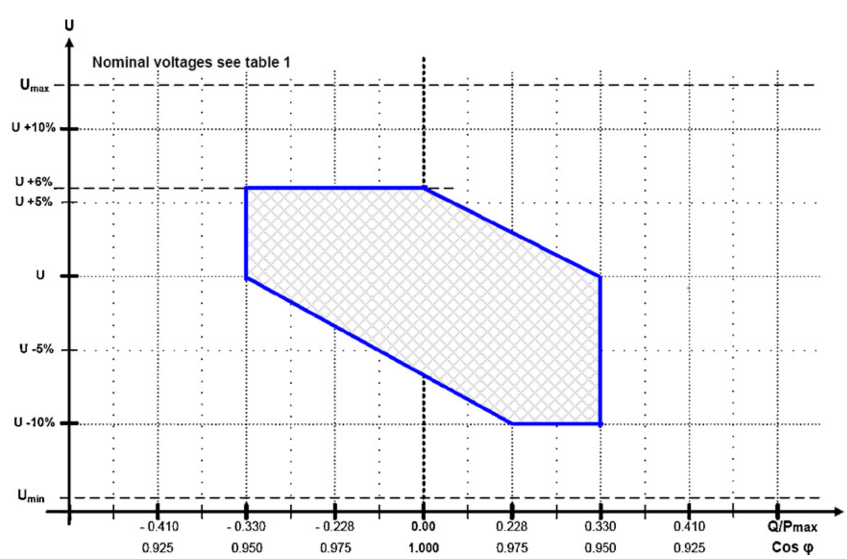

Fig. 8. Voltage regulation requirement enforced by Danish Grid Code.

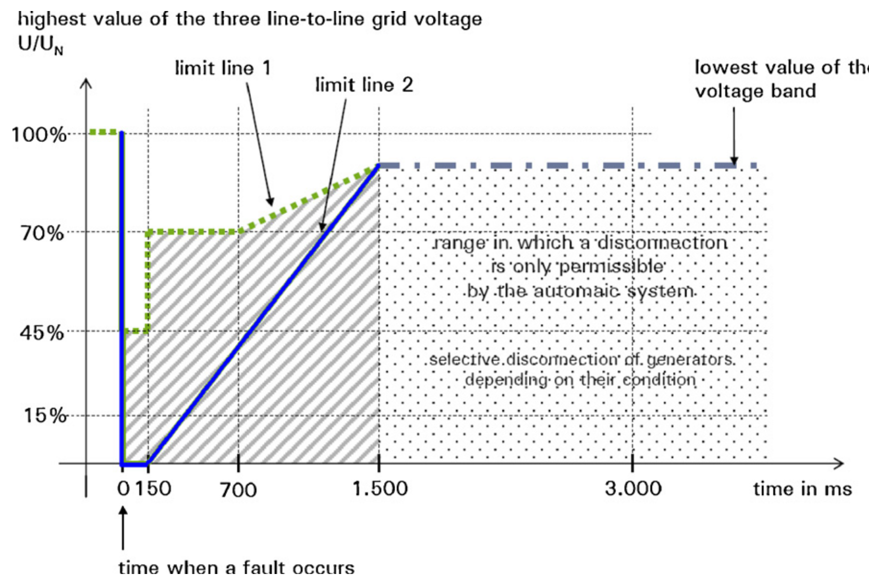

Fig. 9. German LVRT requirement.

Table 2
LVRT requirements in international grid codes.

Grid code country	During fault		Fault clearance	
	V_{min} (PU)	T_{max} (s)	V_{min} (PU)	T_{max} (s)
Australia	0.0	0.1	0.7	2
Canada	0.0	0.15	0.85	1
Denmark	0.2	0.5	0.9	1.5
Germany	0.0	0.15	0.9	1.5
Ireland	0.15	0.625	0.9	3
New Zealand	0	0.2	0.6	1
Spain	0.0	0.15	0.85	1
UK	0.15	0.14	0.8	1.2
USA (FERC)	0.15	0.625	0.9	3
USA (WECC)	0.0	0.15	0.9	1.75

Table 3
HVRT requirements in international grid codes.

Country	During swell	
	V_{max} (PU)	T_{max} (s)
Australia	1.3	0.06
Denmark	1.2	0.1
Germany	1.2	0.1
Spain	1.3	0.25
USA (WECC)	1.2	1

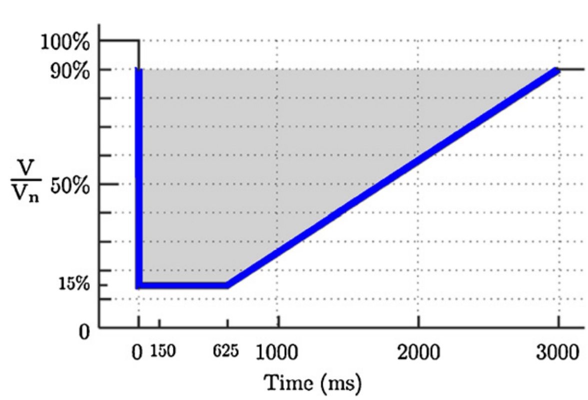

Fig. 10. Irish/American LVRT requirement.

The regulations on the reactive power support of wind farms during voltage disturbances are included in the grid codes of Australia, Denmark, Germany, Ireland, Spain and UK. Australian Grid Code requires WPPs to provide capacitive reactive current equal to 4% of their maximum continuous current for each 1% reduction in the PCC voltage, when the voltage drops to less than 90% of its rated value. This means that WPPs must generate their maximum reactive current when the PCC voltage reduces by more than 25%. Danish and German Grid Codes have defined similar requirement, but they demand for 2% of the reactive current injection for each percent reduction in the PCC voltage, i.e., maximum reactive current will be needed when the PCC voltage drops to less than 0.5 PU (see Figs. 11 and 12). In Spain, wind farms must also be fitted with a voltage control loop that injects reactive current during three-phase faults according to the characteristic shown in Fig. 12. The adopted control loop must reach its set-points within two fundamental periods after the fault occurrence. Finally, British and Irish Grid Codes state that WPPs must produce their maximum reactive current during a voltage dips caused by a grid fault without exceeding the safety limits of WPPs.

Regulations on the active power recovery of WPPs are defined in Australia, Ireland, Germany, Spain and UK. Australian Grid Code requires WPPs to restore their active power output to 95% of the prefault value within 100 ms after the fault clearance. In Ireland, WPPs must continue the active power production during the fault period in proportion to the retained voltage. Also, the active power output must restore to 90% of the maximum available power within 1 s after the voltage recovery to 0.9 PU. German Grid Code stipulates active power restoration to the prefault value immediately after the fault clearance, with the gradient larger than 20% of the rated power per second. In Spain, WPPs are not allowed to consume active power during the fault and the voltage recovery periods. Also, WPP must retain the power generation during the fault period in proportion to the remnant voltage. Finally in UK, WPPs must restore their active power output to 90% of the prefault value with 500 ms after the supply voltage recovery to 90% of the nominal value.

Based on the *P*–*Q* requirements discussed in the above, it can be seen that there are some situations when the WPP has to be overloaded to fulfill both active and reactive current requirements enforced by the grid codes. Under these circumstances, the active or reactive current component must be prioritized against its counterpart in order to constrain the output current of wind generators

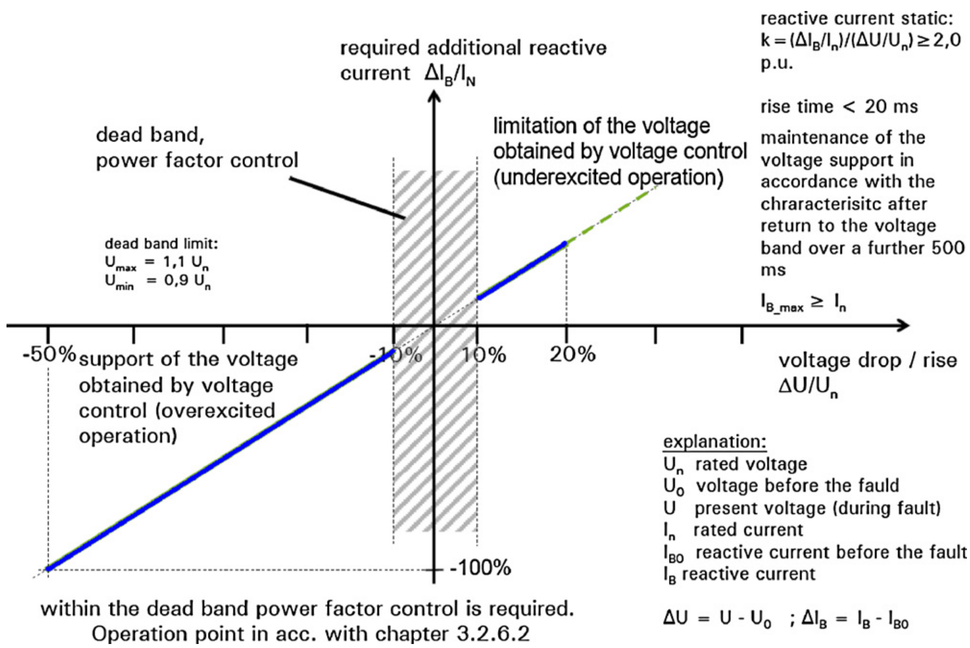

Fig. 11. Reactive power support requirement enforced by German Grid Code.

within the design limits. In Australia and Germany, the reactive current component has the highest priority under fault condition. The opposite situation applies to the grid codes of Ireland, Spain and UK.

3.3. Extended range of frequency–voltage variations

International grid codes require large WPPs to continuously operate within the extended range of frequency–voltage variations. In Australia, WPPs must operate infinitely within the frequency range of 49.5–50.5 Hz and the voltage range of 90–110%. They must also withstand the frequency variations in the range of 49–51 Hz for 10 min, within the frequency range of 48 and 51 Hz for 2 min, and within the frequency range of 47.5 Hz and 52 Hz for 9 s. The frequency–voltage range defined in Danish Grid Code is shown in Fig. 2. Similar regulations are enforced by Transpower and Nordel, as shown in Figs. 13 and 14, respectively. Other countries have defined extended frequency ranges as listed in Table 4. It is evident that the most onerous transient frequency limits are outlined in Canada (with 7.5% reduction permitted for 0.35 s), whereas the continuous frequency variations in the British Grid Code appears to have the widest range ($47.5 < f < 52.0$ Hz).

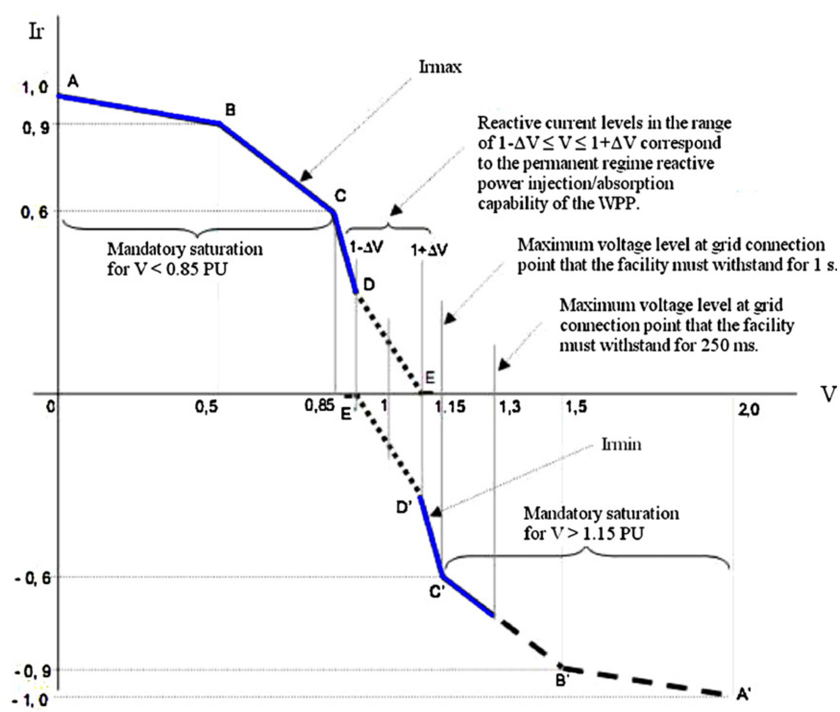

Fig. 12. Reactive power support requirement enforced by Spanish Grid Code.

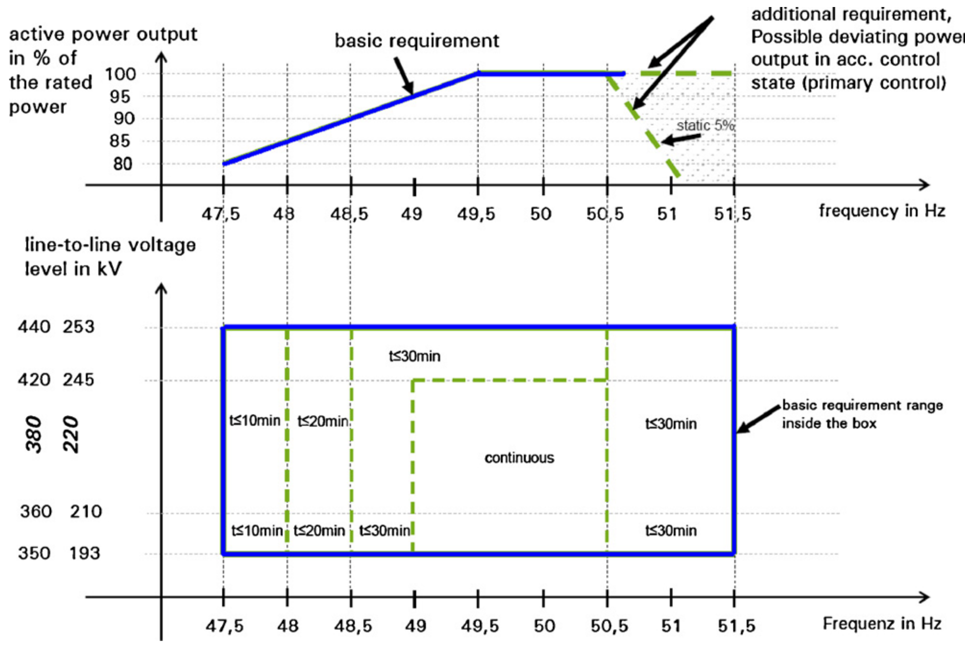

Fig. 13. Frequency–voltage variations range defined by Transpower.

3.4. Active power control and frequency regulation

According to the international grid codes, WPPs must control their active power output in response to the frequency variations and thereby, provide the frequency regulation facility to the system operator. There is no direct control on the prime mover of wind generators; therefore, these generation units are usually exempted from active power increase that is needed in the case of frequency drop. However, the active power output of WPPs must be curtailed during frequency rise such that it helps regaining balance between the network generation and consumption. Production curtailment in WPPs can be attained either through shutting down some wind generators or pitching the blades of wind turbines. Danish and German regulations on the active power control of WPPs are shown in Figs. 6 and 13 respectively. Fig. 15 shows the Irish requirement, where Points B and C denote the range of normal operating conditions. That is, power control action must be taken for the frequency range outside $49.7 < f < 50.3$ Hz. It is finally worth mentioning that Energinet (the Danish TSO) usually practices the gradient power constraint for some offshore wind farms (e.g., Horns Rev wind farm located in the North Sea) to gain active power increase capability that would be needed to stabilize the grid frequency when it drops to below the nominal value.

3.5. Reactive power control and voltage regulation

Modern grid codes require WPPs to control their reactive power generation and, in turn, offer voltage regulation service to the network operator. Danish requirements on the reactive power control capability of WPPs are shown in Figs. 7 and 8. According to the Australian Grid Code, WPPs must be able to continuously operate at their rated output power with the power factor varying from 0.93 capacitive to 0.93 inductive, based on the command signal received from the system operator. In Canada, the reactive power requirements are defined under continuous and dynamic operating conditions. WPPs must be able to continuously work with the power factor varying from 0.9 capacitive to 0.95 inductive, whereas the minimum range for dynamic conditions varies from 0.95 capacitive to 0.985 inductive. Canadian Grid Code also requires WPPs to have a voltage regulation system that acts under the voltage set-point control mode. This voltage control loop must be calibrated to achieve 95% of the reference reactive power in 0.1–1 s after the

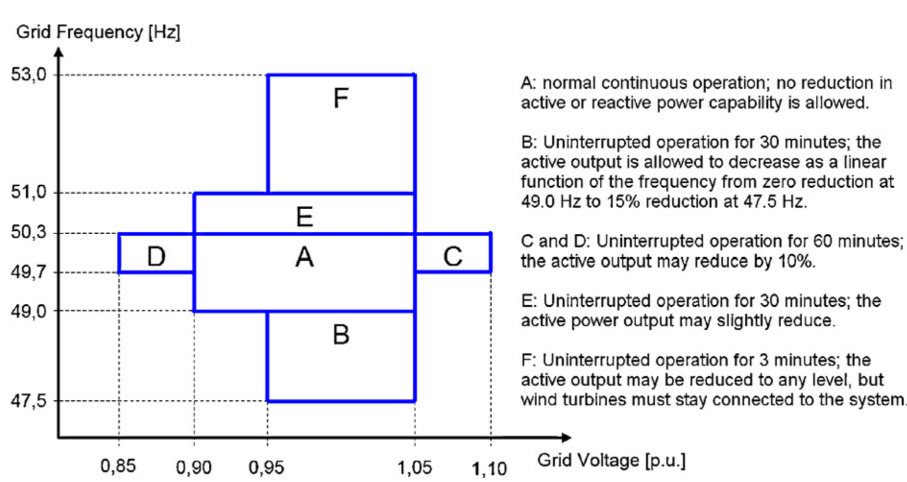

Fig. 14. Frequency–voltage variations ranges defined by Nordel.

Table 4
Frequency limits in international grid codes.

Country	Frequency limit (Hz)	Maximum duration
Australia	49.5 < f < 50.5	Continuous
	49.0 < f < 51.0	10 min
	48.0 < f < 51.0	2 min
	47.5 < f < 52.0	9 s
Canada	59.4 < f < 60.6	Continuous
	58.5 < f < 61.5	11 min
	57.5 < f < 61.7	1.5 min
	57.0 < f < 61.7	10 s
	56.5 < f < 61.7	2 s
	55.5 < f < 61.7	0.35 s
Denmark	48.5 < f < 51	Continuous
	48.0 < f < 51.0	25 min
	47.5 < f < 52.0	5 min
	47.0 < f < 52.0	10 s
Germany	49.0 < f < 50.5	Continuous
	48.5 < f < 51.5	30 min
	47.5 < f < 51.5	10 min
	46.5 < f < 53.5	10 s
Ireland	49.5 < f < 50.5	Continuous
	47.5 < f < 52.0	60 min
	47.0 < f < 52.0	20 s
UK	47.5 < f < 52.0	Continuous
	47.0 < f < 52.0	20 s

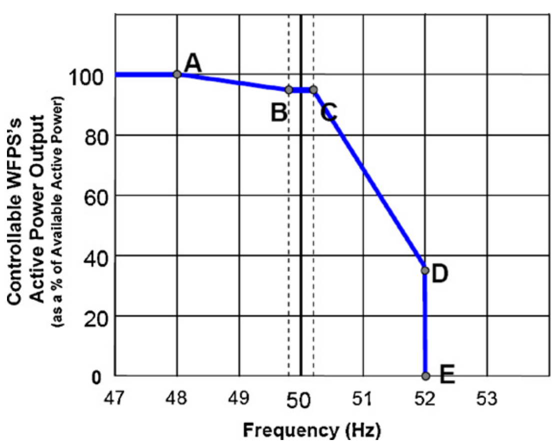

Fig. 15. Power curtailment requirements enforced by Irish Grid Code.

step change in the voltage set-point. In Germany, WPPs must be able to operate with the power factor in the range of 0.95 inductive to 0.925 capacitive depending on the PCC voltage, as shown in Fig. 16, respectively. The reactive power regulations for other countries are summarized in Table 5. Note that in Germany, Spain, and UK, reactive power control changes as the PCC voltage reduces or increases from the rated value (as shown for German Grid Code in Fig. 8). Therefore, comparing the international regulations of the reactive power control of wind farms is not possible as some grid codes consider the variation of the supply voltage.

Table 5
Power Factor limits in international grid codes.

Grid code country	Power factor	
	Cap.	Ind.
Australia	0.93	0.93
Canada	0.9	0.95
Denmark	0.95	0.95
Germany	0.95	0.925
Ireland	0.95	0.95
New Zealand	0.95	0.95
Spain	0.91	0.91
UK	0.95	0.95
USA	0.95	0.95

4. Global harmonization and future trends of the regulations

4.1. Global harmonization of grid codes

The study presented in Section 3 shows that connection requirements for large WPPs can vary substantially from one system operator to another. These regulations are often not sufficiently clear, technically justified or economically sound. This has reportedly resulted in gross inefficiency and additional costs imposed on wind turbine manufacturers and wind farm developers. The European Wind Energy Association (EWEA) has urged European system operators to set their new grid codes in a more consentient manner to achieve harmonized regulations throughout the global market. Consistency in the regulations would assist wind turbine manufacturers to move from 'market-oriented' products to 'universal' solutions. At the present time, wind turbine manufacturers are constantly challenged to adapt their hardware and software designs according to the specific requirements of each country, rather than developing a globally optimized design. This trend must change in the near future when the global wind power installation is projected to immensely increase. Besides that, harmonization of the international grid codes will assist system operators to share their experience and learn from past operating incidents experienced by other system operators. This will clearly create a win–win situation for both system operators and wind power manufacturers.. British and Irish grid codes require WPPs to provide the reactive power support according to the characteristics shown in Figs. 17 and 18

EWEA has proposed a two-step scheme to harmonize the international grid codes, including *structural harmonization exercise* and *technical harmonization exercise*. In the first step, a generic grid code format is to be established where the structure, designations, figures, method of specification, definitions and units are fixed, explicit and agreed upon. The structural harmonization is not aimed to equalize the numerical values of technical requirements set by different system operators, but to fit all the regulations into one unique format. Then in the next step, EWEA recommends international system operators to reduce dissimilarities between their requirements through adopting more consistent numerical values for each connection requirement. It must be noted that EWEA proposes the harmonization exercises, especially the second step, as gradual processes that should take place over a period of 2–5 years. The minimum transition period of 18 months is recommended before any revisions or new requirements become obligatory for the wind farm developers. EWEA also advises that new regulations should not be applied to the WPPs that have already obtained connection agreements. Changes or upgrades of wind farms to fulfill new requirements shall be voluntary with additional incentives or payments for the wind farms owner.

Besides globally harmonized regulations, it is highly recommended that international grid codes should avoid posing costly requirements on WPPs unless these regulations are truly needed for the secure operation of electrical networks. An optimal balance between cost and technical requirements would help wind farm developers to attain more economically viable solutions, which at the end benefits the consumers. The cost-benefit analysis of regulations is especially crucial for the inclusion of fault ride-through regulations because posing this requirement can increase the overall of cost a wind turbine by more than 5% [16].

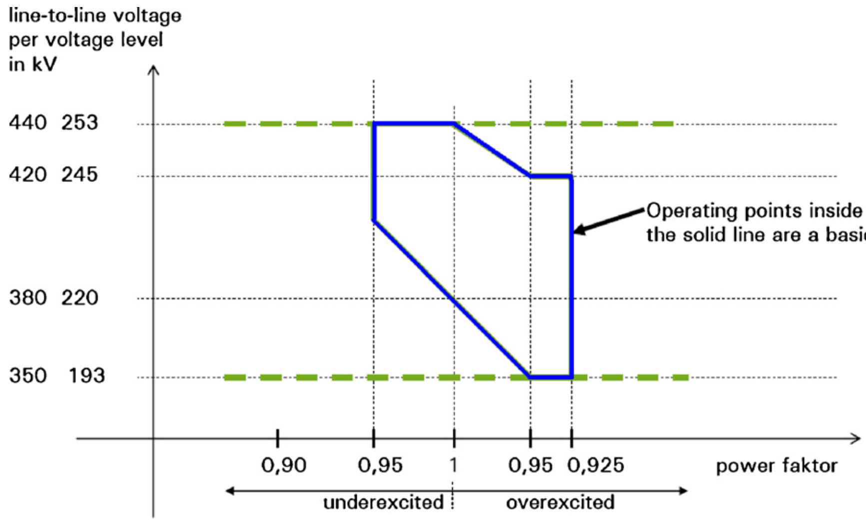

Fig. 16. Power factor control requirement enforced by German Grid Code.

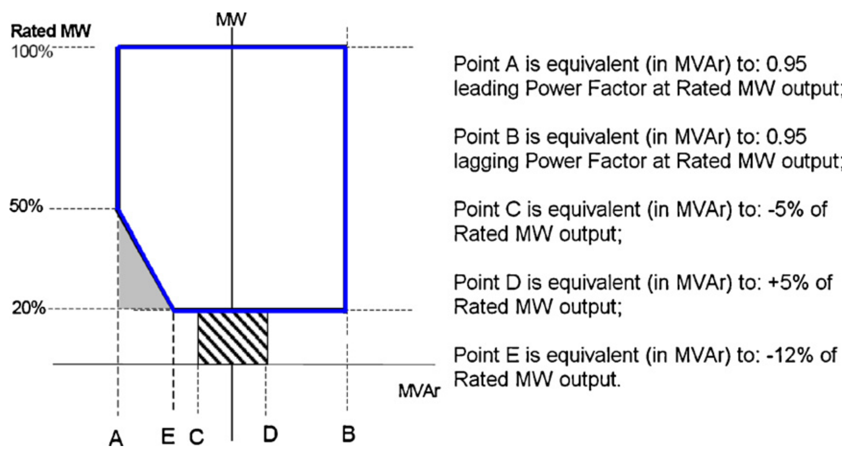

Fig. 17. Reactive power control requirement enforced by British Grid Code.

4.2. Future trends in technical requirements

Studying the latest drafts of international grid codes shows that more stringent requirements are to be imposed on large WPPs. Specifically, future wind farms will be required to (1) provide reactive power support during the fault period, (2) emulate inertia response, and (3) provide power oscillations damping.

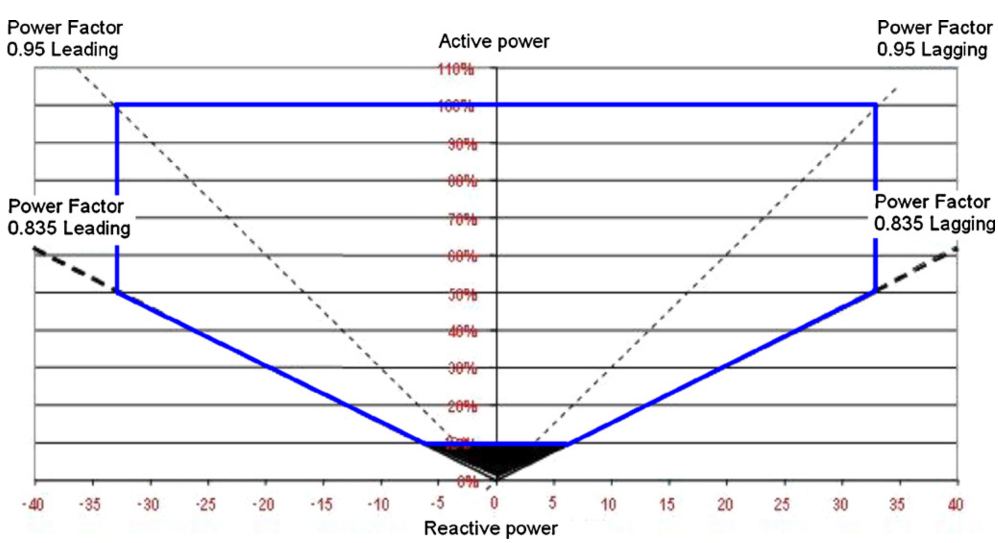

Fig. 18. Power factor control requirement enforced by Irish Grid Code.

The reactive power support facility of WPPs is already requested in the grid codes of Australia, Denmark, Germany, Ireland, Spain and UK. Recent research studies, backed with practical reports from system operators, shows that modern variable-speed wind turbines boast very versatile reactive power control capability which can be effectively utilized to enhance the short- and log-term voltage stability of the adjacent network. Therefore, emerging grid codes are increasingly demanding WPPs to exploit this superior control capability to support the network stability under various types of disturbances in the grid [17].

On the other hand, variable-speed wind turbines are connected to the main grid through back-to-back voltage-source converters, so the "natural" inertia response is minimal [18]. In other words, WPPs cannot provide the synchronizing power characteristics during frequency deviations, as do conventional synchronous generators. This would result in a twofold impact: (1) the angular acceleration of synchronous generators increases and larger restoring forces would be needed to restore the disturbed machines back to the equilibrium, and (2) the rate of frequency decay and nadir of frequency decline would increase upon the loss of generation events. To address these problems, Spanish and Irish Grid Codes have recently recommended large WPPs to have the ability to emulate the inertia response similar to the synchronous generators. The supplementary control loop adopted to serve this purpose must act on the frequency variations as the input and change the output active power accordingly to suppresses the frequency deviations. The inertia response requirement is not compulsory at the present time, but it is expected to be included in the future grid codes of Spain, Ireland, New Zealand and Australia. Spanish Grid Code, for instance, recommends an auxiliary proportional-integral (PI) control unit to emulate the inertia response with the following specifications: (1) the derivative constant of the PI controller (K_d) must be adjustable between 0 and 15 s; (2) the gains of PI controller must be adjusted such that the active power output can increase by 5% within 50 ms; (3) energy storage devices of any technology must be used to assist the WPP to inject or absorb at least 10% of its output active power for at least 2 s; (4) the deadband of frequency variations is equal to $\pm$10 MHz; (5) the inertia response controller must be disabled for the voltage sags of below 0.85 PU; and (6) changes in the gains of PI controller must be achievable depending on the evolution the network situation [19].

Future grid codes will also require large WPPs to participate in damping the power oscillations with the low frequency of 0.15–2.0 Hz. To provide the power system stabilizer facility, WPPs must integrate an additional lead-lag control loop that acts on the power oscillation (probably at remote area) as the input signal and increase/decrease the wind power output in the opposite direction such that it damps the power system oscillations. Recent studies have proven that variable-speed wind turbines can present superior power system stabilizer response compared to the conventional generation system [20].

5. Compliance technologies

The ability of WPPs to meet the international grid codes is greatly influenced by the technology used in the wind farm. Fig. 19 shows three topologies that have been widely used in wind generation systems [1]. The simplest technology (type A) is constituted of a squirrel cage induction machine directly connected to the grid. This technology is referred to as a fixed-speed wind turbine because the machine slip can change in the very limited range of $\pm$1%. Soft-starter is needed to avoid large inrush current at the machine starting instant. Also, reactive power compensation devices, e.g., capacitor banks or STATCOM, must be installed to locally provide the machine magnetization. The aerodynamics of fixed-speed wind turbine can be controlled by stall, active-stall or pitch control approaches [1].

In type B, a wound rotor induction machine is used and an adjustable resistance is connected to the rotor winding. The torque characteristic of the machine can be altered through the variable rotor resistance. As a result, the machine speed can vary in a limited range of $\pm$10% around the synchronous speed; however, the slip power will be dissipated in the resistance as heat. Therefore, the overall system performance is low and sizeable heat sinks are needed to avoid thermal instability problems inside the machine structure. This technology was popular in 90s but with the recent advances in power electronic converters, it has becomes obsolete. Type B wind generator is not studied in this paper.

In type C and type D, back-to-back converters have been used so that the generator speed can vary widely according to the instantaneous wind speed at the site. These technologies are referred to as variable-speed wind generators. Type C is called doubly fed induction generator (DFIG). In DFIG-based wind generators, a wound rotor induction machine is mechanically coupled to the turbine through shaft and gear-box system. The three-phase stator winding of the machine is directly connected to the grid, whereas the rotor winding is connected via back-to-back voltage source converters (VSCs) rated at 30–35% of the generator size. This gives a rotor speed variation range of about $\pm$25%. The rotor-side converter (RSC) controls the active and reactive power outputs from the machine, while the grid-side converter (GSC) regulates the dc-link voltage at the reference value. The DFIG-based wind generators have recently become the most dominant technology in the market as they offer many technical and economical advantages, including maximized power capture, reduced mechanical stresses imposed on the turbine, improved power quality, and reduced acoustical noise.

In type D, the stator winding of a synchronous or induction generator is connected to the grid through fully rated back-to-back VSCs. The machine-side converter (MSC) controls the active and reactive power outputs of the machine. The GSC, on the other hand, maintains the dc-link voltage at its setpoint and controls the reactive power exchange with the grid, i.e., the GSC transfers the active power extracted from the wind turbine to the grid at an adjustable power factor. Cost-benefit analysis of wind turbines shows that the gear-box costs about 15% of the total wind turbine price and it reportedly has the highest failure rate between the electrical and mechanical components of a wind generation system [21]. Therefore, multi-pole permanent magnet synchronous machines have recently become popular as they avoid gear-box. Moreover, since the machine excitation is not provided via the slip-ring system, the permanent magnet machine needs less monitoring and maintenance operations. This can be a major advantage for offshore wind farms, where access to the wind generators is extremely laborious.

5.1. Fault ride-through capability

Fault conditions impose no major threat on the electrical parts of type A wind generators because this technology does not employ power electronics converters. However, at the fault onset, the electromagnetic torque of the machine reduces proportional to the square of the remnant voltages. This can result in the rotor acceleration beyond the safety limits of the machine, unless the supply voltage restores rapidly or the input mechanical torque from the wind turbine reduces. Besides that, since the machine slip increases during the fault period, the active power output of the wind generator reduces notably and it reactive power absorption rises. As a consequence, not only cannot this technology fulfill the reactive injection requirements during the fault period, but it exacerbates the voltage sag condition by absorbing reactive power.

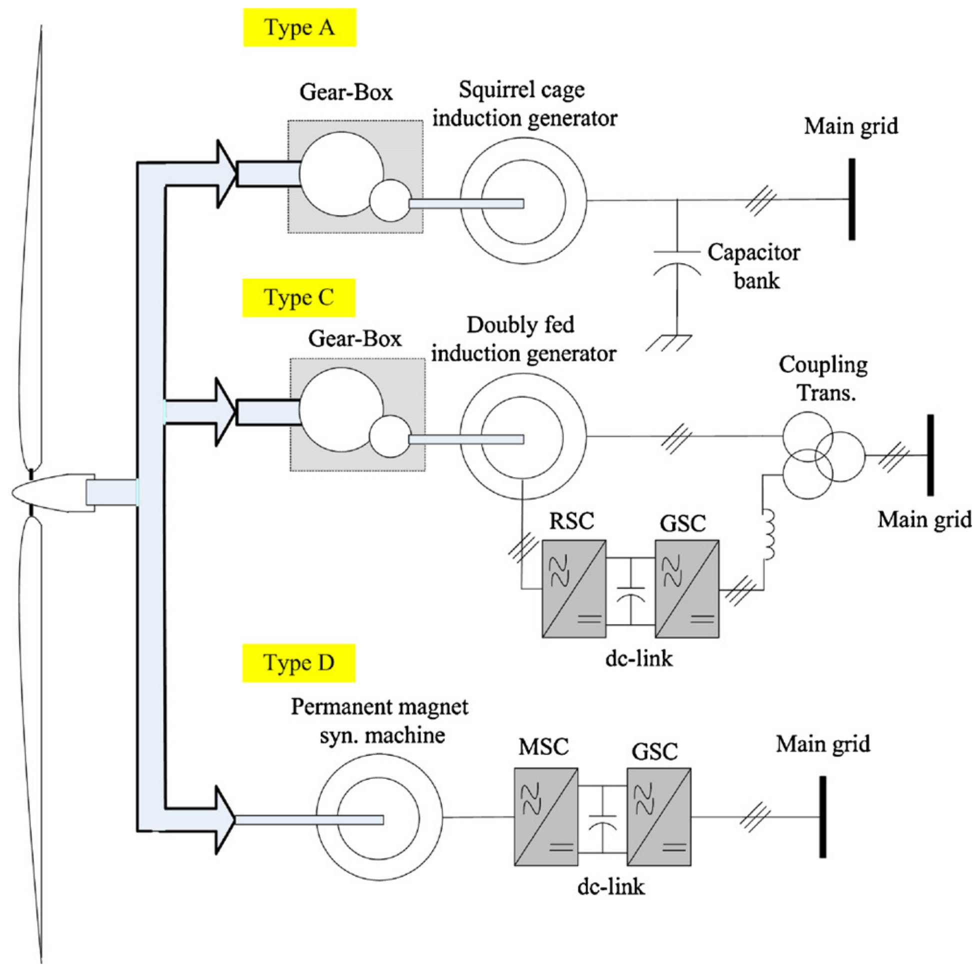

Fig. 19. Different wind generator technologies.

The LVRT capability of type A wind generators can be improved through using commercially available FACTS devices [22–29], fast pitching of the turbine blades during the fault period [30], using dynamic breaking resistors [31–33], or implementing superconducting magnetic energy storage (SMES) [34–36]. Ali et al. have conducted a comparative study on various transient stability enhancement methods proposed for fixed-speed wind generation systems [37]. It was shown that the pitch control system is the cheapest solution, but it has very slow dynamic response due to the mechanical constraints of the system. STACOM and braking resistor were found to be simple and cost-effective solutions under various types of fault. Finally, SMES is found to be the most effective solution for not only LVRT capability enhancement, but also reducing the voltage and power fluctuations under steady-state conditions. SMES is very expensive, however.

Compared to type A, variable-speed wind generators have the distinctive advantage of independently controlling their active and reactive power outputs thanks to their power electronic converters. Therefore, generators type C and type D can potentially fulfill more strict regulations on power curtailment and reactive power control as well as the provision of inertia response and power system stabilizer facility [17,20]. However, the main difficulty associated with the operation of types C and D is their transient response under fault conditions. The fault ride-through capabilities of DFIG-based wind generators is very limited because the stator and rotor windings of the machine are magnetically coupled and as a consequence, large inrush currents in the stator winding causes destructive overcurrents in the semi-conductor switches of the RSC [38]. The power-electronic switches (e.g., IGBTs) are very vulnerable to overcurrents and appropriate protection schemes must be taken to address this problem. The most popular method to protect the RSC from harmful overcurrents is to place a short circuit on the rotor slip rings during the fault period, using the so called crowbars [39–41]. However, once the crowbar is engaged, the machine controllability will be lost and DFIG resembles a high-resistance squirrel cage induction machine. This temporary configuration is the worst-case combination of poor active power output and high reactive power demand, which can severely exacerbate the fault condition [1,39]. As a result, the reactive power support during the fault period or fast active power recovery after the fault clearance cannot be attained using crowbars. To avoid these problems, additional converters/dynamic resistors [42–47] and modified ride-through control strategies [48–55,102] are suggested in the literature. Both solutions (specifically the latter) increase the cost and complexity of DFIG-based wind generators. Large overshoot of the dc-link voltage is the other difficulty that hinders successful fault ride-through response of DFIG-based WPPs. The dc-chopper and modified control scheme for the GSC are suggested to overcome this problem [56–57,103].

Full-converter wind generators have better ride-through capability in comparison with the DFIG topology because the machine operation is completely decoupled from the grid through back-to-back VSCs. Therefore, voltage sag or swell conditions have no direct impacts on the generator. The only crucial problem is the large fluctuations in dc-link voltage [58]. During the fault period, the GSC capability to transfer the power from the capacitor to the

grid reduces proportional to the voltage sag amplitude, while the power injected from the wind generator stays relatively constant. Due to the large mismatch between the input and output powers of the capacitor, the dc-link voltage is likely increase beyond its safety limits which can potentially force the wind turbine to disconnect from the grid [38]. Non-linear control schemes, dc-choppers and temporary de-loading schemes are suggested as very effective methods to limit the dc-link voltage variations [58–61]. In [59], coordinated control of a dc circuit braking resistor, the turbine blade pitch angle and converters' operation has been proposed to protect the mechanical and power electronic components of the wind generator.

5.2. Reactive power support and voltage regulation

The reactive power absorption of fixed-speed induction generators cannot be controlled as the operating point of the machine varies depending on the machine torque. Therefore, compensation devices such as switchable capacitor banks, SVC or STATCOM must be installed within the WPPs so that the grid code requirements on the reactive power control and/or voltage regulations can be fulfilled under various operating conditions [22,24,39,62–63].

In contrast with type A, variable-speed wind generation systems are able to provide a decoupled control of the active and reactive powers – through the *P*–*Q* control loops adopted in their power electronic converters. The reactive power support capability of DFIG-based wind turbines is thoroughly studied in [17,64–70]. Time-domain simulation results show that the reactive power capability of DFIG-based WPPs can be utilized at no extra cost to the wind farm owner to reduce system losses under steady-state condition and to improve the post-fault voltage recovery following a disturbance [104]. The superior voltage regulation performance of DFIG-based WPPs is explored in [71,72]. For type D technology, the VSCs are sized at the nominal machine capacity; hence, this topology can present better reactive power support capability compared to the DFIG concept, as demonstrated in [17,73]. It is also shown that the reactive power output of the variable-speed WPPs can effectively enhance the LVRT capability of the adjacent fixed-speed WPPs [74–76].

5.3. Frequency control, inertia response and power system stabilization

The responses of fixed- and variable-speed wind generators to network frequency disturbances are thoroughly studied during the last decade. There is a consensus in the literature that fixed-speed WPPs have inherent inertia response that counteracts the network frequency deviations and, in turn, contributes to the primary frequency support [77–79]. In contrast, the operation of variable-speed WPPs are inherently decoupled from the network frequency as in these technologies, the active and reactive power outputs of the generator are directly controlled via its power electronic converters [18,80–91]. Therefore, large penetration level of variable-speed WPPs would negatively affect the total inertia of the power system if no modifications are applied to their control schemes [18,87–90]. Supplementary control loops are proposed to address this problem. In these methods, the power required to emulate inertia response and provide primary frequency support is usually extracted from the kinetic energy stored in the rotating mass of the turbine blades [86]. Recent studies demonstrate the superior performance of variable-speed WPPs in the provision of primary frequency support, compared to the conventional synchronous generators [80,87,90]. In [92,93], partial de-loading, e.g., delta production constraint, is practiced for DFIG-based WPPs such that the generation unit can participate in not only primary but also long-term frequency support. Further, auxiliary lead-lag compensators were suggested in the control scheme of DFIG-based WPPs to provide the power system stabilization facility [20,94–96]. Extensive results obtained from eigenvalue analysis and small signal stability studies illustrate that variable-speed WPP can improve the overall system damping much more effective than the conventional synchronous generators equipped with automatic voltage regulator and power system stabilizer [20,97–99]. Finally it is shown that DFIG-based WPPs equipped with supplementary control loops can contribute to suppression of the interarea oscillations as reported in [100–101].

6. Conclusions

So far the grid code developments have been heavily influenced by instincts of utility engineers and isolated anecdotal experiences. A more consolidated approach in the area of grid connection regulations is required in future, addressing factors such as penetration level of wind power, network redundancy and robustness, and short circuit level at the PCC. A global taskforce involving engineers, operators, manufacturers and researchers would be very much desirable to formulate and benchmark grid codes based on operating expansions and technology opportunity cost benefit ratio. It is also important not to impose unnecessary cost premium on wind farm developers, as this will ultimately have to be passed on the consumer. Emerging grid codes are however expected to include stringent requirements on reactive power injection, inertia response and power oscillation damping.

Acknowledgment

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